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EXPERIMENTAL STUDIES ON THE OPERATION OF AGRICULTURAL CROPS MOWING UNIT WITH SIMULTANEOUS CHOPPING AND INCORPORATION OF STUBBLE INTO THE SOIL

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ABSTRACT

For harvesting crops, one-phase and two-phase methods are most often used. When implementing the second one, mounted and trailed units are used. The latter is becoming less and less used due to the problems with movement stability in the horizontal plane because of the asymmetric layout. A stubble background, which

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swath,
stubble height

is susceptible to solar and wind influences, is formed as a consequence of application of the mounted harvesting unit, As a result, the field's soil in the inter-swath space intensively loses moisture. A harvesting unit based on a tractor with rear steerable wheels has been designed to eliminate this shortcoming. A header is mounted on its front hitch linkage system, and a disc harrow is mounted on the rear one. During the working movement, such a harvesting unit mows the crop into swaths, chops the stubble in the inter-swath space, and simultaneously incorporates it into the soil. This article presents the operation results of such a unit for harvesting winter wheat, oats, and sudan grass. Research has established that oscillations in the deviations of the mowed crops' swaths from a straight line are of low frequency. The variances spectra of this process, as follows from the Analysis of normalized spectral densities, are concentrated in the frequency range of 0-0.5 m^{-1}. The mean value velocities of the harvesting unit are 2.13-2.61 $m \cdot s^{-1}$, which is 0.17-0.21 Hz. The variances of oscillations in the header operating width, the cut crop's swath width, and the disc harrow's width are concentrated in approximately the same low-frequency range, the maximum value of which is small and does not exceed 0.9 m^{-1} or 0.37 Hz. The oscillation processes of the mowed crops' stubble height have a higher frequency. The cutoff frequency of their normalized spectral densities is at the level of 3.0 m^{-1}. In terms of time, considering the harvesting unit movement velocity of 2.13-2.61 $m \cdot s^{-1}$, this is 1.02-1.25 Hz. At the same time, oscillations in the stubble height of mowed crops are characterized by small variances, the maximum value of which does not exceed 11 cm^2.

Introduction

The world practice knows several ways of harvesting grain crops. The most popular are one-phase and two-phase methods. Each has advantages and certain disadvantages in specific natural and climatic zones (Chongyou et al., 2014; Gawłowski et. al., 2020, Rudoy et al., 2021; Abdi et. al., 2022; Nadykto et al., 2023). Therefore, their Analysis and evaluation allow the agricultural producer to make the final choice in favor of one of these methods.

Trailed and mounted harvesting units implement the two-phase method of harvesting cereal crops, forage grasses and rapeseed. The former includes a self-propelled vehicle (usually a tractor) and a trailed windrower (Bulgakov et al., 2018a; Konstantinov et al., 2019; Undersander et al., 2011). Since the latter is located to the tractor's right, its traction resistance creates a momentum that turns the entire harvesting unit in a horizontal plane clockwise (Bulgakov et al., 2018b). As studies have shown (Bulgakov et al., 2019a), this leads to a deterioration in the stability of the unit's plane-parallel movement and the quality indicators of its work. Because of this, such trailed units are used less and less.

Mounted units can also be asymmetrical (Jinfeng et al., 2021; Rudoy et al., 2021; Shinners et al., 2012). However, the transverse displacement of the windrower relative to the longitudinal axis of the self-propelled vehicle symmetry is so insignificant (Bulgakov et al., 2019b) that such harvesting units differ little from symmetrical ones (Caixia et al., 2015; Foster et al., 2005; Gesce, 2004; Jin et al., 2022). It should be noted that using mounted units with a hydraulic drive of the working bodies makes it possible to increase their efficiency (Panchenko et al., 2018; Panchenko et al., 2019; Voloshina et al., 2021, Boryga, 2023).

The essence of the problem is that after the passage of a trailed and/or mounted harvesting unit, the remaining stubble of the harvested crop does not protect the soil from intense moisture evaporation. To avoid this, following the fieldwork regulations, the stubble must be chopped and incorporated into the soil no later than 2-3 days after harvesting the crop. However, in practice, there is a significant delay in this operation. At the same time, according to field studies, its timely implementation makes it possible to ensure soil moisture conservation within 2–6 mm. When the agricultural crop stubble is chopped simultaneously with its mowing, it can achieve conservation and subsequent soil moisture accumulation. In practice, attempts are known to implement this technological method with a unit as part of a combine harvester and a trailed cultivator. However, the latter's presence significantly complicates the harvesting unit's reverse movement while maneuvering the headland. Such a system's motion dynamics have not been studied, so neither its diagram nor design parameters are substantiated.

Our practical experience tells us that the front harvester and the rear tillage machine must be mounted. To do this, we have designed a harvesting unit consisting of a tractor on the front hitch linkage system, in which a header is placed, and a disc harrow on the rear one. Preliminary theoretical studies have established that for better stability and controllability of such a unit's plane-parallel movement, the header and disc harrow should be attached to the tractor without the possibility of their rotation relative to each other in the horizontal plane. Such a constructive solution is provided by check chains of the tractor's front and rear hitch linkage systems. At the same time, the tractor has rear steerable wheels, for which its control post has been deployed at 180 degrees in the cab, and the gearbox has been set to reverse movement mode.

At the same time, the quality indicators assessment of such combined unit functioning is entirely absent. Available scientific information shows ways to solve this problem using separate headers and cultivators (harrows). Thus, the loss determination of oilseed rape seeds during its swath mowing has been studied in some detail (Chengqian et al., 2012; Ping et al., 2014; Price et al., 1996). Statistical evaluation of fluctuations in the width and height of this crop's swaths and its stubble was carried out with a change in the header conveyor velocity (Yitao et al., 2014; Zhuohuai et al., 2021). Extensive studies have been conducted to choose the working disk body type when chopping and incorporating rice stubble and stalks (Xu et al., 2023), winter wheat (Wang et al., 2020), etc., into the soil.

In this study, the technological operations execution of swath mowing crops and chopping their stubble together with soil in the inter-swath space was carried out by a single unit. Research has established that the largest reserves of available moisture are accumulated in the soil precisely during its shallow (26.4 mm) cultivation with disk working devices (Kyryliuk et al., 2020). Subsequently, this contributes to obtaining a higher yield of agricultural crops grown in this field.

In connection with the above, this article aims to determine the unit's performance indicators for mowing crops into swaths with simultaneous chopping of the stubble in the inter-swath space. These indicators include the header's mowing width, stubble height, width and straightness of the swath, chopping width of the disc harrow and disking depth.

Material and methods

The physical object of research was a harvesting unit (Fig. 1a) consisting of a wheeled tractor with a rigid frame HTZ-16131 (Kharkiv, Ukraine), a ZhVN-6 header (Berdyansk, Ukraine) and a mounted disc harrow BDN-3 (Belotserkivmaz, Ukraine). As noted above, the specified tractor was converted to a reverse driving mode, in which its front steered wheels were located in place of the rear ones. The header had a special adapter to be attached to the tractor (Fig. 1b).

A b

Figure 1. General view of the harvesting unit (a) and adapter (b) for attaching the header to the tractor

The header and the harrow were fixed from their turn relative to the tractor's symmetry longitudinal axis. The harvesting unit's brief technical description is presented in Table 1.

Table 1.
Harvesting unit technical characteristics

Index	Value
Tractor weight (kg)/power engine (kW)	8200/117.6
Tractor wheel track (m)	2.1
Tractor wheelbase (m)	2.86
Tractor wheels	16.9R38
Header weight (kg)	1290
Header operating width (m)	6.0
Disk harrow weight (kg)	620
Disk harrow operating width (m)	3.1

The harvesting unit studies were conducted during mowing in swaths of three crops: winter wheat, oats, and Sudan grass. Before researching each harvested field, the following initial characteristics were determined: i) soil moisture and density in a layer of 0−15 cm; ii) plant height of each crop and its biological yield; iii) weed density.

Three sites were allocated in each field to conduct studies in triplicate. Each site was 250 m long. The first 50 m of the site was used to accelerate the harvesting unit. On the remaining 200 m, the following parameters were measured: i) time for the unit to pass the scoring site, s; ii) header operating width, m; iii) deviation of the crop swath from a straight line, m; iv) stubble height, cm; v) crop swath width, m; vi) disc harrow operating width, m; vii) disc harrow tillage depth, cm.

The instruments, as well as the method of their use for determination of the soil moisture and density, are described in detail in the article (Adamchuk et al., 2020). The weed density and yield of crops were determined using a wooden frame with an area of 1 m^2. The distance between 30 measurement zones performed along the site diagonal was at least 10 m. The mass of weeds, wheat and oat grains that got into the frame area after threshing their ears was determined using the Axis AD 200 device (made in Poland) electronic scale with a measurement error of 0.001 g.

The harvesting unit operating velocity at each site was calculated by the formula: $V_o = 200 \cdot t^{-1}$ ($m \cdot s^{-1}$) (t is the time of passage of the collection unit through the settlement zone). We used an electronic stopwatch KHP PC3860 (made in China), with a measurement error of 0.01 s to register it.

Before the harvesting unit movement, 200 pegs were installed at a distance h_i from the mowed crop array with a step of 1 m to determine the header operating width. After the unit passage, the distance (L) from each peg to the wall of the remaining array of mowed crops was measured (Fig. 2). The operating width of the header (B_p) was determined from the following equation:

$$B_p = L - h_i \tag{1}$$

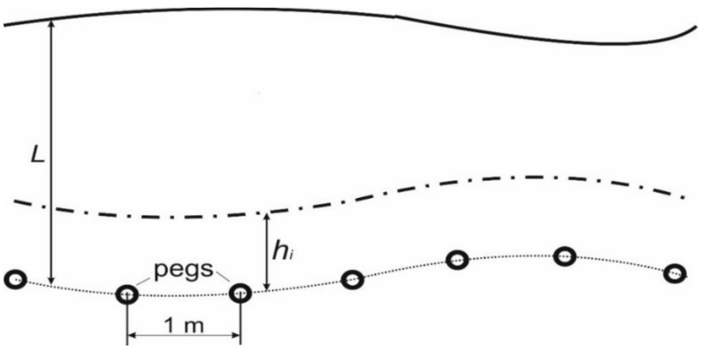


Figure 2. Diagram for determination of the header operating width:

(-··-··-) – the array of the crop before the harvesting unit passage;
(—) – the array of the crop after the harvesting unit passage

Figure 3. Kit for measuring tillage depth

The depth of tillage with a disc harrow was measured on the site in two repetitions with a measurement step of 0.2 m, the number of measurements was 300. To measure the depth of tillage, a measuring set (Fig. 3) was used, the basis of which is an ultrasonic sensor HC-SR04 (made in China) and an Arduino UNO board (made in Italy) (measurement error no more than 0.5 cm).

The height of the stubble of the mown crop was measured along the length of the plot with a ruler (error ±0.5 cm) with a step of 0.2 m, the number of measurements was at least 250. To measure the width of the swath and the width of the grip of the disc harrow, measuring tapes of the 2nd accuracy class with lengths of 2 and 5 were used m, respectively. The number of measurements of these parameters with a step of 1 m was at least 150.

The data obtained were used to calculate such statistical characteristics as the mean, variance, and normalized spectral density of oscillations of random processes under study.

Results and discussion

The conditions for conducting experimental studies of the harvesting unit for mowing in swaths of winter wheat, oats, and Sudan grass are presented in Table 2.

The harvesting unit operating velocity in each of the three fields depended on the yield of the harvested crop: the higher the level of the second, the lower the value of the first (Table 3).

In this case, the oscillations in the swaths trajectory deviations of the mowed crops from a straight line have a rather low-frequency character. As the Analysis of normalized spectral densities showed, the main variance spectra of this process for winter wheat, oats, and Sudan grass are concentrated in the frequency range of 0–0.5 m^{-1} (Fig. 4). At mean harvesting unit velocities of 2.13–2.61 $m \cdot s^{-1}$, this is 1.065–1.305 s^{-1} or 0.17–0.21 Hz.

Table 2.
Characteristics of the experimental sites

Index	Value for crop		
	Winter wheat	Oats	Sudan grass
Soil moisture in a layer of 0-15 cm (%)	19.3	18.8	20.4
Soil bulk density in a layer of 0-15 cm ($g \cdot cm^{-3}$)	1.16	1.22	1.23
Crop height (m)	0.70±0.05	0.74±0.03	0.69±0.08
Crop yield ($t \cdot ha^{-1}$)	4.5	3.8	3.9
Weed density ($g \cdot m^{-2}$)	15±5	23±7	35±9

The calculated value of Cochran's test for the compared variances of oscillations in the trajectories' deviations of mowed crop swaths from a straight line (see Table 3) is 0.347. Since this is less than the tabular value equal to 0.393, the hypothesis (null) about the equality of the compared variances at the statistical significance level of 0.05 is not denied. This result confirms the sufficiently high harvesting unit movement stability with a fixed header and disc harrow attachment to the tractor in a horizontal plane.

Table 3.
The mode and performance of the harvesting unit

Index	Value for crop		
	winter wheat	oats	Sudan grass
Unit operating velocity (m·s^{-1})	2.42±0.05	2.61±0.03	2.13±0.06
Header operating width, B_p (m)	5.86±0.05	5.88±0.06	5.90±0.04
Stubble height (cm)	14.6±0.8	15.8±0.7	13.6±0.4
Stubble height variance (cm^2)	10.44	8.96	7.56
Swath width, B_s (m)	1.35±0.09	1.42±0.08	1.18±0.07
Disc width, B_d (m)	3.1±0.1	3.0±0.1	3.0±0.1
Disc depth (m)	7.8±0.2	8.1±0.3	7.0±0.5
Swath trajectory oscillation variance (cm^2)	20.56	21.08	22.13

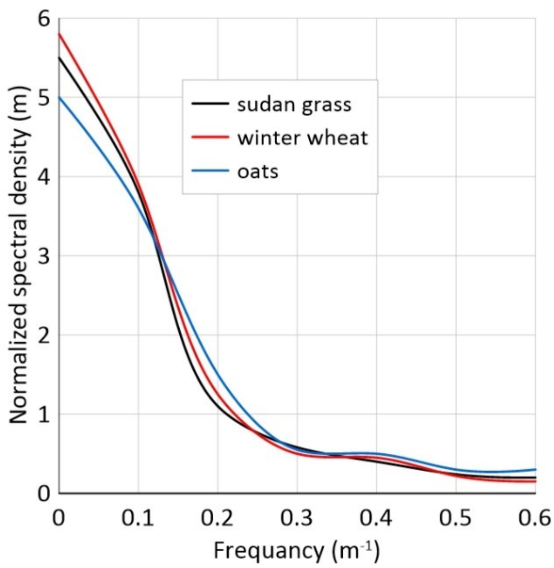
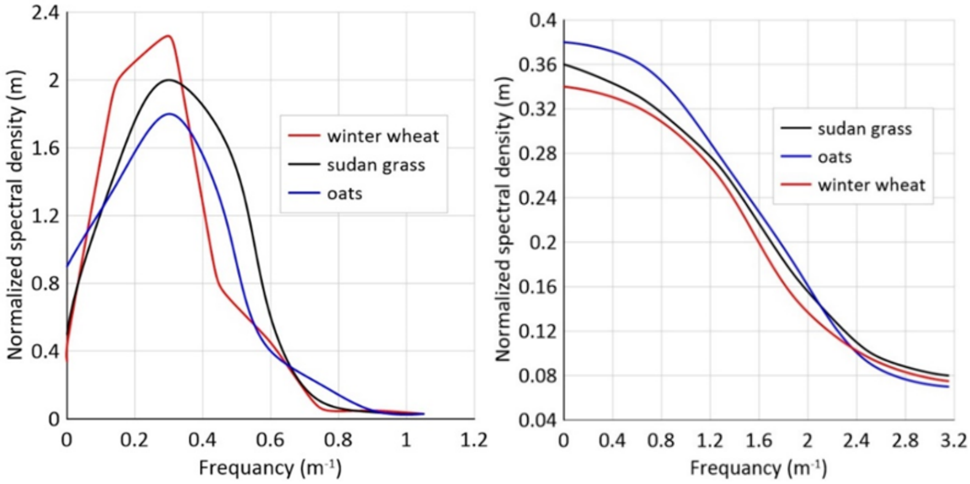


Figure 4. Normalized spectral densities of mowed crops swaths' deviations of trajectories from a straight line

The high straightness of the crop swaths is, to some extent, a result of the stable header operating width. The mean value of this parameter varied between 5.86-5.90 m (Table 3). Concerning the nature of the change in the normalized spectral densities (Fig. 5), the main spectrum of this parameter oscillations can be considered as low frequency. This is confirmed by the fact that it (the spectrum) practically does not exceed the range of 0–0.75 m^{-1} for all crops. At the harvesting unit, the operating velocity is 2.13-2.61 m·s^{-1}, which is 0.25-0.31 Hz.

The normalized spectral densities maxima of the header operating width oscillations fall approximately at the same frequency, equal to 0.3 m^{-1} (Fig. 5a). If the harvesting unit were less stable in the horizontal plane, then the value of this parameter could be much larger, and the range of its oscillations could be much wider.

Compared to the header operating width fluctuations, the mowed crops' stubble height oscillation processes have a higher frequency. The cutoff frequency of their normalized spectral densities is 3.0 m^{-1} (Fig. 5b).



ab

Figure 5. Normalized spectral densities of header operating width oscillations (a), of crops stubble height oscillations (b)

In terms of time, considering the harvesting unit operating velocity of 2.13-2.61 $m \cdot s^{-1}$, this is 6.39-7.83 s^{-1} or 1.02-1.25 Hz. Compared to the same statistic parameters for the header operating width (see Fig. 5a), this is 3-4 times greater. On the other hand, stubble oscillations in mowed crops are characterized by a small variance (Table 3). Moreover, the null hypothesis about their equality at a statistical significance level 0.05 is not denied. This statement is supported by the calculated value of Cochran's test (0.387), which is less than the tabular value of 0.393.

Due to their intrinsic nature, the swaths' width oscillations of mowed crops should also be attributed to low-frequency ones. This result is confirmed by the fact that almost all variances' spectra of this parameter are concentrated in the frequency range of 0-0.8 m^{-1} (Fig. 6). This almost coincides with the frequency range in which the header operating width variances are concentrated (see Fig. 5a).

During the harvesting unit operation, the disc harrow chops and mixes the stubble with the soil in the inter-swath area (Fig. 7). Under the experimental conditions, the tillage depth of the agrotechnical background, depending on the harvested crop, was 7.0-8.1 cm (see Table 3). In a soil layer of this thickness, the capillary structure is completely broken, which causes a decrease in moisture evaporation until the harvesting of the mowed crop swaths.

Due to the sufficiently high stability of the harvesting unit in the horizontal plane, the disc harrow working width oscillations are characterized by relatively low frequencies (Fig. 8).

The cutoff frequency of the normalized spectral densities of this parameter oscillations is approximately 0.9 m^{-1} or 0.31–0.37 Hz. This result is comparable to similar ones obtained for oscillations in the header operating width and the mowed crops' swaths width.

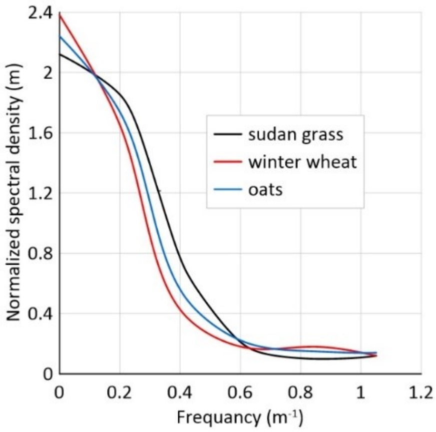


Figure 6. Normalized spectral densities of swaths width oscillations

Figure 7. Background of the inter-swath space after the harvesting unit passage

The swath formed by the header was placed on the stubble. Part of this stubble was placed in a strip along each side of the swath. The mean value of this strip width (B_z) can be determined from the equation:

$$B_Z = 0{,}5 \cdot \left(Bdmindmaxsminsmaxpmin_{pmax}\right) \quad (2)$$

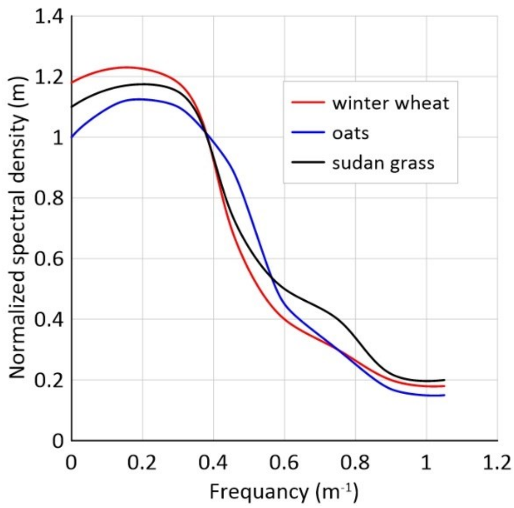


Figure 8. Normalized spectral densities of the soil cultivated strip width oscillations in the inter-swath space of mowed crops

This equation uses the maximum and minimum mean values of the parameters presented in Table 3. Calculations using them show that, under experimental conditions, the value of the B_z parameter along each side of the mowed crop swath was at least 0.5 m (Fig. 8). As it turned out later, this was quite enough to prevent lumps of soil from getting into the swath after chopping the soil with a disk harrow of the harvesting unit.

Conclusions

Experimental studies have established that harvesting unit movement stability in a horizontal plane as part of a tractor with rear steerable wheels, a front header attached to it, and a disc harrow hung at the rear can be considered satisfactory. This is evidenced by the following results obtained when mowing winter wheat, oats, and Sudan grass with the indicated unit:

– oscillations in the trajectory deviations of the crops swaths from a straight line are low-frequency since the variance spectra of this process, as follows from the Analysis of the corresponding normalized spectral densities, are concentrated in the frequency range of 0-0.5 m^{-1}. At mean velocities of the harvesting unit 2.13–2.61 $m \cdot s^{-1}$, this is 1.065–1.305 s^{-1} or 0.17–0.21 Hz;
– according to Cochran's test, the zero hypotheses about the compared variances equality in the mowed crops swaths deviations oscillations from a straight line is not denied at a statistically significant level of 0.05;
– fluctuations variances in the header operating width, the swathes width, and the disc harrow operating width are concentrated approximately in the same low-frequency range, the maximum value of which is small and does not exceed 0.9 m^{-1} or 0.37 Hz;

– the oscillation processes of the mowed crops' stubble height are characterized as more high-frequency. The cutoff frequency of their normalized spectral densities is 3.0 m^{-1}. In terms of time, considering the harvesting unit movement velocity 2.13-2.61 $m \cdot s^{-1}$, this is 6.39–7.83 s^{-1} or 1.02-1.25 Hz. At the same time, oscillations in the stubble of mowed crops are characterized by small variances, the maximum value of which does not exceed 11 cm^2.

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BADANIA EKSPERYMENTALNE NAD DZIAŁANIEM ZESPOŁU ŻNIWNEGO Z JEDNOCZESNYM MŁÓCENIEM I INKORPORACJĄ ŚCIERNISKA DO GLEBY

Streszczenie. Do zbioru upraw często stosuje się metody jedno i dwu - fazowe. W drugiej metodzie wykorzystuje się zespoły zawieszane i przyczepiane. Te ostatnie używane są coraz rzadziej ze względu na problemy ze stabilnością ruchu w płaszczyźnie poziomej wynikające z asymetrycznej konstrukcji. W wyniku zastosowania zawieszanego zespołu żniwnego powstaje ściernisko, które jest podatne na wpływ słońca i wiatru. W rezultacie gleba na polu w przestrzeni między pokosami intensywnie traci wilgoć. Aby wyeliminować tę wadę, zaprojektowano zespół żniwny oparty na ciągniku z tylnymi kołami skrętnymi. Na przednim układzie zawieszenia zamontowany jest heder, a na tylnym brona talerzowa. Podczas ruchu, taki zespół żniwny kosi uprawę tworząc pokos, rozdrabnia ściernisko w warstwie między pokosami i jednocześnie wprowadza je do gleby. Niniejszy artykuł przedstawia wyniki pracy takiego zespołu podczas zbioru pszenicy ozimej, owsa i sorga sudańskiego. Badania wykazały, że oscylacje w odchyleniach pokosów koszonych roślin od linii prostej mają niską częstotliwość. Spectrum odchyleń tego procesu, jak wynika z analizy znormalizowanych gęstości spektralnych, mieszczą się w zakresie częstotliwości 0-0,5 m^{-1}. Średnie wartości prędkości jednostki koszącej wynoszą 2,13-2,61 $m \cdot s^{-1}$, to jest 0,17-0,21 Hz. Odchylenia oscylacji szerokości operacyjnej zespołu przedniego, szerokości pokosu uprawy oraz szerokości brony talerzowej mieszczą się mniej więcej w tym samym zakresie niskiej częstotliwości, której maksymalna wartość jest niska i nie przekracza 0,9 m^{-1} lub 0,37 Hz. Procesy oscylacyjne wysokości ścierniska skoszonej uprawy mają wyższą częstotliwość. Częstotliwość ich znormalizowanych gęstości spektralnych jest na poziomie 3.0 m^{-1}. Biorąc pod uwagę prędkość ruchu zespołu żniwnego 2,13-2,61 $m \cdot s^{-1}$, wynosi ona 1,02-1,25 Hz. Jednocześnie, oscylacje wysokości ścierniska skoszonej uprawy charakteryzują się niskimi odchyleniami, maksymalna wartość których nie przekracza 11 cm^2.

Słowa kluczowe: część żniwna kombajnu zbożowego, brona talerzowa, pokos, wysokość ścierniska